than locomotives.) The remaining number was reduced by 50% to exclude employees who were located at maintenance facilities other than "back shops" [DeHague, 1980]. The balance was reduced by 11% to exclude salaried supervisors, coach cleaners, and stores laborers. As described previously, the resulting number for the years 1950–1960 was reduced by the percentage of steam locomotives in service. These data are listed in Table VI.

A summary of the employment data for all of the previously mentioned occupations is given in Table VII for five-year intervals. The data are quite stable for the years 1950–1980 and well reflect both employment and its trend with time. One exception is the 1950 value for shipbuilding which is unrepresentative; for the five years, 1948–1952, employment averaged 189,000.

TABLE VI. Employment, Maintenance of Equipment and Stores, Class I Railroads

Year	Numbers of[a] employees (in thousands)	Locomotives[b] in service steam (in thousands)	diesel	Percentage steam	Exposed employees
1940	281	41.1	0.5	98.8	69
1945	387	39.7	3.0	93.0	95
1950	348	26.7	15.4	63.4	54
1955	273	6.3	26.6	19.1	13
1960	184	0.5	29.1	1.7	1

[a]Association of American Railroads, 1940–1960.
[b]Association of American Railroads, Annual, and Interstate Commerce Commission, 1961, 1958,

TABLE VII. Employed Populations Potentially Exposed to Asbestos in Selected Occupations and Industries, 1940–1975

Industry of occupation	Number employed in calendar year (in thousands) 40	45	50	55	60	65	70	75
Primary asbestos manufacturing	23	32	35	37	35	35	32	31
Secondary asbestos manufacturing	30	60	75	75	84	93	108	114
Insulation work[a]	17	27[b]	33	41	47	53	53	55
Shipbuilding and repair	157	175[c]	128[d]	194	184	185	181	177
Construction trades	426	379	741	893	1,102	1,215	1,341	1,029
Railroad engine repair	69	95	54	13	1	0	0	0
Utility services	44	62	62	65	65	64	69	74
Stationary engineers and firemen	295	303	311	348	385	289	291	293
Chemical plant and refinery maintenance	113	194	186	200	188	187	205	200
Automobile maintenance	372	370	647	655	661	800	912	1,100
Marine engineer room personnel (except US Navy)	34	76	37	37	34	35	31	22
Totals	1,880	1,773	2,309	2,558	2,766	2,956	3,223	3,095

[a]Insulators are included here and not in other trades in which they were employed, such as shipbuilding, construction, plant maintenance, or power generation.
[b]Does not include any of the 9,000 temporary wartime insulators in the shipbuilding industry.
[c]Estimate of "permanent" shipyard work force. Does not include any of the 4,325,000 temporary wartime shipyard workers.
[d]Unrepresentatively low value; average for 1948–1952 was 189.

New Entrants Into the Work Force 1940–1980

Data on the number of additions to the employment rolls in various manufacturing industries are reported monthly by the Bureau of Labor Statistics [1979]. However, BLS does not report cumulative annual rates for "new hires." Moreover, the BLS data refer to persons hired by individual establishments in each industry, not the number hired by the industry as a whole. There may be considerable duplication of persons involved in the new hires reported on a monthly basis over a year's time. There is additional duplication involved in counting new hires in a particular establishment who were previously employed in another establishment of the same industry. It was, therefore, necessary for us to develop a measure for estimating the unduplicated new hires in each industry for each year.

This was done by comparing the number of new hires obtained for major industry groups with data available from the continuous work history sample of the Social Security Administration (SSA) for the years 1957–1960 [Galloway, 1967]. Unfortunately, data are only available for major industry groups such as durable and nondurable goods manufacturing, construction, transportation, and services. Detailed information for individual industries is not provided. Information on the number of individuals who were employed in 1960 and were also employed in the same industry in 1957 is given in Table VIII. This allows one to calculate an annual transfer rate from one industry group to another but not from one industry to another within an industry group (eg, from the manufacture of asbestos products to the manufacture of bolts, nuts, and rivets). Bureau of Labor Statistics data on the permanent retirement or death in each of these industries are also available from Bureau of Labor Statistics publications. In a steady state, the SSA separation rate plus the annual rate of retirement and deaths would equal the new hire rate. As three years is a relatively short follow-up, there would be some transfers back to an industry group after the observation period. The correction for this, however, would be relatively small and somewhat compensates for the greater adjustment required to account for transfers between industries within an industry group.

The SSA data are shown in Table IX and compared with the annual rate of new hires from the Bureau of Labor Statistics data for the years 1958–1960, corrected by the increase or decrease in the total work force over the three-year period of time (January 1958–January 1961). The correction consisted of attributing the annualized change in work force between 1958 and 1961 to a change in the number of new hires. Terminations are much less affected by work force changes and then only with severe conditions. The corrections were virtually all less than 10%.

In comparing the data obtained in this manner from the Social Security Administration with that estimated using BLS new hires, fractional employment additions in the chemical industry and oil refinery operation closely matched the fractional number of transfers from the nondurable goods industry (0.166 and 0.132 vs 0.111). For these industries, we will utilize the Bureau of Labor Statistics data on new hires in SIC 28 or SIC 29 reduced by 30% to reflect possible transfers within these respective industries. Transfers are expected to occur inasmuch as the industries are concentrated within geographic areas and movement from one company to another is expected. This reduces the new hire rate for oil refineries to a value less than that for the nondurable goods industry as a whole. However, both oil refinery and chemical manufacturing have much less labor turnover than other industries in the nondurable goods manufacturing segment.

TABLE VIII. **Industry of Major Job: Male Wage and Salary Workers Employed in Both 1957 and 1960 (Based on 1% Sample of Social Security Administration Data)***

Wage and salary workers employed in both 1957 and 1960	Manufacturing			Construction	Transportation, communications, public utilities	Services
	All	Durable goods	Nondurable goods			
All workers whose major job was in this industry in 1957	123,713	78,458	45,255	27,603	22,507	30,019
Industry of major job in 1960 the same as in 1957	102,854	63,676	34,653	19,280	17,906	20,778
Annualized "permanent" separations from work sector	0.063	0.072	0.093	0.127	0.079	0.130

*Source: Interindustry Labor Mobility in the United States 1957 to 1960 [Galloway, 1967].

TABLE IX. The Average Fractional Number of New Hires Entering a Specific Industry Group Each Year During the years 1958–1960

Industry	Change of industry from SSA continuous work history	Retirements and deaths	Annual permanent transfers from industry	BLS data on new hires	SIC group used for BLS estimate
All manufacturing	0.063	0.018	0.081	0.280	20–39
Durable goods manufacturing	0.072	0.018	0.090	0.265	24–25, 32–39
Primary asbestos products				0.343	329[a]
Secondary asbestos products					
Heating equipment				0.240	343[b]
Boiler shops				0.290	3443
Furnaces and ovens				0.159	356
Electrical housewares				0.199	363
Shipbuilding and repair				0.432	3731
Construction	0.127	0.020	0.147		15–17
Insulation work (IAHFIAW)				(0.030)	
Other construction workers				NA	
Nondurable goods manufacturing	0.093	0.018	0.111	0.303	20–23, 26–31
Chemical plant maintenance				0.166	28
Oil refinery maintenance				0.132	29
Transportation and public utilities	0.079	0.020	0.099	NA	491–493
Marine engine room personnel				NA	
Services (stationary engineers)	0.130	0.025	0.155	NA	
Auto mechanics	0.130	0.013	0.142	NA	

[a]New hires were estimated using durable goods new hires adjusted for the relationship between 329 and durable goods for the years 1972–1979.
[b]Production work force for the years 1958–1960 was based on durable goals and the relationship between 343 and durable goods for the years 1972–1979.
NA, not available.

For primary and secondary asbestos manufacturing, it would be expected that there would be less transfer between similar companies. This occurs because of the widespread geographical distribution of the respective plants. Individuals terminated by one company would unlikely be hired by another manufacturer in the same industry. Thus, we will adopt a value for the new hires in primary and secondary manufacturing that would be equal to 80% that of the Bureau of Labor Statistics data. It would be expected that a greater percentage of terminated shipyard employees would be rehired by other yards or by the same yard at some later date. This occurs because of the highly fluctuating nature of shipyard business, depending as it does upon large contracts of uncertain frequency. Thus, for shipyard employees we will adopt a value of 50% of the Bureau of Labor Statistics' new hires rate for SIC 3831. The rate of new hires for 1958–1960 is, thus, 0.216. This compares with 0.138 estimated by the US Navy for naval shipyards in these years. The agreement is reasonable as turnover in government shipyards is considerably less than in civilian yards.

Individuals employed in construction trades (except insulation work), stationary engineers and firemen, and automobile mechanics are a highly mobile segment of the work force. However, they would tend to maintain employment in their respective trade, simply moving from one employer to another. Therefore, we feel that the Social Security Administration data on labor turnover well represent the members of these industries. It is felt that termination from employment in utility services, however, is less likely to lead to employment in a corresponding industry and data on new hires using Social Security Administration information would underestimate the actual percentage. Thus, we have increased the SSA new hires estimate by 50%. The sources of all new hire data are listed in Table X. For those industrial segments where the numbers of new hires are not provided, the new hires for all manufacturing are utilized adjusted by the ratio of new hires as determined by Social Security Administration data, 1958–1960, to new hires in the corresponding years for all manufacturing.

The number of new hires for insulation workers will utilize the data on new entrants into the insulation workers' union from their membership (column 1 of Table III). We will use the same acquisition data proportionately for the nonconstruction insulators, as data from the chemical and refining industry indicate average employment periods nearly equal to those of insulators. However, the turnover for those on permit and employed as nonunion workers is likely to be considerably higher. We have no information on what their turnover may be relative to union insulators but a value twice as great would appear to be reasonable. To account for this, we will increase the IAHFIAW new hires by 0.8 to account for permit workers, by 2.0 to account for nonunion new hires and by 1.2 for nonconstruction insulators. Thus the total insulator new hires will be five times the IAHFIAW US new members. The 9,000 wartime shipyard insulation workers employed for one year are also included in the new hires for the 1940–1949 decade. Their mortality, however, will be calculated separately as will that of other wartime shipyard workers.

It should be emphasized that these estimates are approximate and subjective. They are felt to be the best basis for estimating the number of new individuals that enter a given industrial segment and are important in estimating the total number of individuals potentially exposed to asbestos. As discussed previously, however, their influence on the total mortality experience from past exposure will be small. A misestimate on the new hires rate will lead to a balancing increase or decrease in the average employment

time. These annual new hire rates were applied to annual employment data for each occupation and industry to arrive at estimates of the number of new persons exposed to asbestos on the job in each year. The data were then cumulated for each decade since 1940. In those industries in which a significant portion of the employees were already included in our tally under an occupational group (asbestos and insulation workers; stationary engineers, stationary firemen and power station operators; or automobile body repairers and mechanics), an adjustment was made to the 1940 industry employment data and new-hires data to remove duplication. These adjustment factors were derived from the BLS National Industry-Occupational Matrix in the case of Asbestos and insulation workers [Bureau of Labor Statistics, 1969b] and the 1970 Census of Population in the case of stationary engineers, stationary firemen and power station operators. No adjustment was necessary for the automobile body repairers and mechanics since the duplication between this occupation and the industries included in this study is insignificant.

An additional adjustment in the new-hires data was made to eliminate the double-counting of persons who were hired in an occupation or industry during the period since 1940 and who had previously been exposed to asbestos in another occupation or industry. We developed an adjustment factor for this purpose by analyzing the occupational histories of 2,544 workers employed in operations exposed to asbestos in cohorts being studied by this laboratory. Table XI lists the percentage of individuals in several study groups with previous substantial exposure to asbestos (equivalent to greater than six months employment in a shipyard). This correction reduces the num-

TABLE X. Source of Annual New Hire Rates by Industry or Occupation

Industry or occupation	Source of annual new hire rates[a]	Average 1958–1961 new hire rates[d]
Primary asbestos manufacturing	0.8 × (SIC 329)[b]	0.294
Secondary asbestos manufacturing	0.8 × (SIC 343, 3443, 356, 363)[b]	0.127–0.232
Insulation	Data from union new entrants used	—
Shipbuilding and repair	0.5 × (SIC 3731)[b] and US Navy data	0.216
Construction trades	1 × (SIC 20–39) × (0.147/0.268)[c]	0.147
Railroad engine repair	1 × (SIC 20–39) × (0.099/0.268)	0.099
Utility services	1.5 × (SIC 20–39) × (0.149/0.268)	0.149
Stationary engineers and firemen	1 × (SIC 20–39) × (0.155/0.268)	0.155
Chemical plant and refinery maintenance	0.7 × (SIC 28)[b]	0.116
	0.7 × (SIC 29)[b]	0.092
Automobile maintenance	1 × (SIC 20–39) × (0.142/0.268)	0.142
Marine engine room personnel	1 × (SIC 20–39) × (0.099/0.268)	0.099

[a]The percentage of various workers within each SIC category, as described in the text, will be used as the basis population for calculating new hires.
[b]Data are utilized for the years available. For years for which new hire data were not published, the new hire data for all manufacturing were used, adjusted by the relationship to the specific SIC code for the years published.
[c]The rate 0.268 is the average annual fraction of new hires in manufacturing for the years 1958–1960, corrected for changes in the work force.
[d]Values for other years are proportional to the new hire rates in the indicated SIC classification.

ber of people ever exposed by 10% (the correction factor used). It will not reduce the mortality, however, as we must account for all person-years of exposure in asbestos-related industries. This will be done by using the adjusted population of new entrants to calculate an average time of exposure (see below) which will overestimate the exposure time by 10% to account for the 10% reduction in exposed populations. It should be emphasized that the uncertainties in either the populations exposed or the average durations of employment greatly exceed 10%

POPULATION AT RISK

The results of the estimation of employment and new-hires at risk are shown in Table XII, indicating that approximately 27,500,000 individuals were potentially exposed to asbestos from 1940 through 1979 in the occupations analyzed. The uncertainties in estimating this number have been described previously, but they cannot be overstressed. The number is an approximation. Further, it includes a large number of individuals whose potential exposure to asbestos would have been of low intensity or of short duration because of high labor turnover (see section on lower risk population). Finally, the term potential should be emphasized. In categorizing a segment of a work force (such as all production shipyard workers) as being potentially exposed to asbestos, some individuals will be included with no actual exposure. On the other hand, individuals in other jobs (such as management) who did have exposure were not counted. The numbers may or may not balance. These uncertainties will be compensated for in the estimates of mortality by using data on the mortality or morbidity of representative work-force segments, which will also include the full spectrum of exposure circumstances.

It should also be noted that a large number of asbestos-exposed individuals are not included in the estimates of Table XII. Important groups with identified risks include family contacts of asbestos-exposed workers, engine room personnel aboard US Navy ships in World War II, and individuals exposed environmentally to asbestos by virtue of residence or work near the use of asbestos. Additional exposures occur to many from the use of asbestos in surfacing materials in schools, night clubs, and auditoriums, or as fireproofing material in office buildings.

Average Duration of Employment

The average duration of employment can be calculated from the fractional new-hire rate adjusted by changes in total work force at different periods in time (see section on methological considerations). Alternatively, the average employment over a decade can be divided by the average yearly number of new hires entering an industry to obtain the average employment time. In essence, this is the period of time that is required for the number of new entrants into an industry to completely replace the work force. These data for the years 1940–1979 are presented in Table XIII and were used for the average durations of exposure in each decade for each industry or occupational group.

Supplemental Labor Turnover Data

The Environmental Sciences Laboratory has access to several seniority lists of work forces employed in asbestos-using industries. These include a large integrated asbestos products manufacturer, a major East Coast shipyard and a plastics polymer plant. Additionally, information on the employment times of all employees in an as-

TABLE XI. Workers Exposed to Asbestos in Five Cohorts Under Study by the Environmental Sciences Laboratory, Mount Sinai School of Medicine

			No. of workers currently exposed	
Location	Industry/occupation	Period	Total	Also exposed in previous employment
Metropolitan New York	Brake repair and maintenance	1979–1980	699	104
Groton, Connecticut	Shipyard	1976	1,024	98
Baltimore, Maryland	Shipyard	1979	286	10
Port Allegany, Pennsylvania	Asbestos products manufacturing	1979	254	21
Quincy, Massachusetts	Shipyard	1979	281	16

TABLE XII. Population at Risk to Asbestos-Associated Disease: Workers Exposed to Asbestos in Selected Occupations and Industries, 1940–1979 (in thousands)

		New entrants				
Industries or occupations	1940	1940–1949	1950–1959	1960–1969	1970–1979	Totals
Primary asbestos manufacturing	23	200	103	86	76	488
Secondary asbestos manufacturing	30	324	227	259	308	1,148
Insulation work[a]	17	35	47	38	47	184
Temporary, World War II		9				9
Shipbuilding and repair	157	433	354	434	383	1,761
Temporary, World War II		4,325				4,325
Construction trades	426	1,786	1,452	1,866	1,975	7,505
Railroad engine repair	69	194	26	0	0	289
Utility services	44	223	116	116	129	628
Stationary engineers and firemen	295	1,136	623	549	510	3,113
Chemical plant and refinery maintenance	104	542	260	239	248	1,393
Automobile maintenance	372	1,884	1,099	1,282	1,779	6,416
Marine engineer room personnel (except US Navy)	34	121	46	40	27	268
Totals	1,571	11,202	4,353	4,909	5,482	27,527

[a]Insulators are included here and not in other trades in which they were employed, such as shipbuilding, construction, plant maintenance, or power generation.

bestos insulation production plant is available. These sources can be utilized for comparison with the data obtained from the Social Security Administration and Bureau of Labor Statistics on labor turnover. They can further be utilized to obtain estimates of the distribution of employment times in a given industry by comparing the number of individuals actually employed to those that were known to have been hired in different time periods. The latter quantity is available from the seniority lists as individuals were

assigned sequential clock numbers upon employment. These data are presented in Table XIV and supplement the turnover data obtained otherwise.

One notable feature is that the asbestos products manufacturer has an extremely high turnover during the first month after hire. This occurs because of terminations of individuals during a one-month probationary period. After that time, the man enters the union bargaining unit, and any individual terminations are subject to grievance procedures. While such practices are not universal, they are certainly not unique, and it is expected that in primary and secondary manufacturing an extremely high turnover will result during the first month or two of employment as individuals are screened for their performance and suitability for a job. In contrast, in construction, shipbuilding, automobile maintenance, and other industries that require a skill, the turnover in early periods of time is expected to be less as an individual would have demonstrated professional competence prior to being hired. Further, he would likely be represented by a union before employment with a given employer. Thus, nonarbitratable dismissals are less common.

TABLE XIII. The Average Employment Time of All Individuals Potentially Exposed to Asbestos, 1940–1979

	Average duration of employment (years) calendar periods			
Industry or occupation	1940–1949	1950–1959	1960–1969	1970–1979
Primary asbestos manufacturing 1.6	1.6	3.5	3.8	4.0
Secondary asbestos manufacturing	2.0	3.5	4.0	3.8
Insulation work	13.7[a]	12.4	15.9	12.5
Shipbuilding and repair	4.3[a]	5.3	4.2	4.6
Construction trades	3.3	8.3	7.5	4.5
Railroad engine repair	4.4	7.7	—	—
Utility services	2.8	5.7	5.7	6.0
Stationary engineers and firemen	2.7	6.3	5.8	5.7
Chemical plant and refinery maintenance	3.7	7.4	8.7	8.1
Automobile maintenance	2.7	6.0	7.7	7.0
Marine engineer room personnel (except US Navy)	4.7	7.4	7.8	6.1

[a]Does not include short-term wartime shipyard workers.

TABLE XIV. Labor Turnover in Selected Industrial Establishments

Establishment	Time period	Number of individuals considered	Number employed by time after hire: 1 year	6 months	2 months	1 month
Shipyard products	1977	1,449	—	73%	80%	—
Asbestos products manufacture	1965–1966	759	37%	—	51%	53%
Asbestos products manufacture	1961–1962	306	42%	—	45%	48%
Asbestos products manufacture	1957–1958	108	27%	—	52%	75%
Plastics production	1961–1962	17	—	100%	100%	100%
Insulation products manufacture	1941–1945	820	38%	53%	82%	93%

A study of workers exposed to brominated chemicals in three plants provides data on the distribution of employment times of all 3,579 individuals employed in the facilities [Wong, 1981]. It substantiates the presence of a large number of individuals with very short employment times. Of all employees, 16.4% worked for less than one month and an additional 28.5% for 1–5.9 months. The full distribution of employment times can be characterized by a two-component decreasing exponential. Thus, the work force can be considered as made up of two groups. The average employment time of one, consisting of approximately 2,200 individuals, was 0.5 years and of the other, with 1,400 individuals, was 11.7 years in good agreement with the data of Table XIII.

Relative Risk by Industry

To calculate the asbestos-related cancer mortality in a given industry or operation, it is necessary to have an absolute or relative measure of exposure for the employee group. While detailed information is not available on the asbestos air concentrations that have been prevalent in previous years in each of the above industries, estimates can be made of the relative risk of death from asbestos exposure on the basis of a variety of other studies. In the calculation of asbestos-related cancer mortality for a given industry or occupation, we will utilize the available data for insulation workers for the dose and time dependence of asbestos cancer. To translate available data for insulation workers to other industries, it is necessary to establish measures of exposure for the different groups considered at risk relative to that of insulation workers. These *relative risks for equal times of employment* will be determined by three indices. The primary one is the directly measured mortality data, especially that of mesothelioma or lung cancer, in an industry or trade. A second is the directly measured average concentrations of asbestos that can be attributed to the work activity. The third is the prevalence of X-ray abnormalities after long-term employment in an industry. Here, we will assume that the percentage of X-ray abnormalities attributable to an exposure circumstance after 20 years of employment will be proportional to the total dose of asbestos inhaled by the workers in that industry. Where the percentage of abnormal X-rays approaches 100%, the relative risks will be determined using the percentages of X-rays having a category 2 or greater abnormality on the ILO U/C scale. Information on these direct and indirect measures is shown in Table XV along with the sources of the various data.

For industries in which none of the above indices are available (construction, railroad steam engine repair) or for which the data are very uncertain, relative risk estimates were made from the numbers of mesotheliomas identified among individuals in different asbestos exposure circumstances compared with the total work force exposed. These data utilized the nationwide survey of mesothelioma in 1972 and 1973 by McDonald and McDonald [1980]. The numbers from this series are shown in Table XVI.

The relative risks, by industry, estimated from all of the above data, are listed in Table XVII. Also Indicated in Table XVII are the principal data sources considered in the relative risk estimates. The data available for the estimates are limited and the estimates are necessarily approximate. For the years 1972–1979, the relative risks for manufacturing, insulation work, shipbuilding, and utility employment will be reduced to 0.1, and those of the other industries (except automobile maintenance) to 0.05 to re-reflect the adoption of control measures. Further, exposures subsequent to 1979 will not be considered.

TABLE XV. Indices of Relative Asbestos Exposure in Selected Occupations and Industries

Industry of occupation	Estimated average fiber concentrations	Relative risk of lung cancer	Percentage of deaths from mesothelioma	Applicable employment period (years)	Percentage of: parenchymal abnormalities 1 +	Percentage of: parenchymal abnormalities 2 +	Percentage of: pleural abnormalities	Applicable employment period (years)
Primary manufacturing	20–40	2.8[a]–6.1[b]	2.6[b]–9.1[a]	1–20 +				
Insulation work	15[a]	4.8[c]	8.7	20 +	85[d]	42[d]	56[e]	20 +
Shipbuilding and repair	2[f]	1.6[g]		2–3	86[h]	17[h]	54[h]	20 +
Chemical plant and refinery maintenance		1.5[i]		15 est	33[j]	3[j]	44[j]	20 +
Automotive maintenance	0.1–0.3[k]				5[k]			10 +
Marine engine room personnel							16–20[l]	15

[a] [Nicholson, 1981a.]
[b] [Seidman et al, 1979.]
[c] [Selikoff et al, 1979.]
[d] [Selikoff et al, 1965.]
[e] [Selikoff, 1965.]
[f] [J. Thorton, quoted in Enterline, 1981.]
[g] [Blot et al, 1981.]
[h] [Selikoff et al, 1981.]
[i] [Hanis et al, 1979.]
[j] [Lilis et al, 1980.]
[k] [Nicholson, 1982.]
[l] [R.N. Jones, 1980.]

TABLE XVI. The Numbers of Mesotheliomas by Work Activity in North America (1960–1972, Canada; 1972, USA)*

Occupation or industry	Number of cases
Primary and secondary manufacturing	21
Insulation work	27
Shipbuilding and repair	21–49[a]
Construction trades	45–76[b]
Railroad engine repair	5
Utility services	
Stationary engineers and firemen	13 +
Chemical plant and refinery maintenance	3
Automobile maintenance	11
"Heating trades"	59[c]

*[McDonald and McDonald, 1980].
[a]Highest number only includes some insulators and heating trades workers.
[b]Highest number may include some insulators, shipyard workers or individuals with employment in heating trades.
[c]Includes many individuals that would be assigned to other categories, as stationary engineers and firemen (furnace repair), shipyard employment (welders, steamfitters), utilities (plumbing, heating, boiler work), manufacturing (boilermakers).

TABLE XVII. The Risk of Asbestos Cancer Relative to Insulation Work After 25 Years Employment

Occupation or industry	Risk	Source of data for estimate
Primary manufacturing	1	Group mortality data, exposure measurements
Secondary manufacturing	0.5	Exposure measurements
Insulation work	1	Reference population
Shipbuilding and repair (except insulators)	0.5	Group mortality data, prevalence of X-ray abnormalities
Construction trades[a] (except insulators)	0.15–0.25[b]	No. of mesothelioma cases in general population
Railroad engine repair	0.2	No. of mesothelioma cases in general population
Utility services	0.3	No. of mesothelioma cases in general population
Stationary engineers and firemen	0.15	Prevalence of X-ray abnormalities
Chemical plant and refinery maintenance	0.15	Prevalence of X-ray abnormalities, group mortality data
Automobile maintenance	0.04	Prevalence of X-ray abnormalities, exposure measurements
Marine engine room personnel (except US Navy personnel)	0.1	Prevalence of X-ray abnormalities

[a]See test for percentage of construction population considered at risk.
[b]Risk for years 1958–1972 when the use of sprayed asbestos fireproofing was common.

The relative risks in Table XVII for insulation work, manufacturing, utility services ("heating trades") shipyard employment, and construction yield "population" risks virtually identical to those found by McDonald and McDonald [1980] in their case-control analysis. They found values of 46.0, 6.1, 4.4, 2.8, and 2.6, respectively, for the relative risks of the above populations. Multiplying our equal exposure risks by

the average durations of employment of all workers from 1940 through 1969 (13.2, 2.0, 4.7, 1.9, and 6.4 years, respectively) and further dividing the risk for construction workers by two to account for the 50% of workers to whom we attributed no risk, we obtain for the relative "population" risks the values, 13.2, 1.3, 1.4, 0.95, and 0.5. Adjusting to the McDonald and McDonald [1980] risk of 46 for insulators, we obtain for "population" risks, 46.0, 4.6, 4.9, 3.3, and 1.8.

Lower Risk Population

While we are unable to obtain full data on the distribution of employment times in all industries, the information depicted above allows us to identify a segment of the work force with considerably less exposure to asbestos. Taking a period of employment of two months in primary manufacturing or insulation work as a measure of a low exposure, we have estimated the number of individuals with such an exposure among the 27,500,000 individuals identified previously. This would correspond to a total exposure of 2–3 f-yr/ml (12–18 f/ml × 1/6 yr). The estimates were made assuming 40% of the new hires in primary and secondary manufacturing and 20% of the new hires in other industries left within two months. For longer periods, we utilized an exponential function, $e^{-\beta t}$, for the distribution of employment times where β is the average steady-state permanent separation rate. The period of employment characterizing "lower exposure" for a given industry will be inversely related to the relative risk of the industry (Table XVII). These data are presented in Table XVIII and suggest that 8,700,000 of those potentially exposed to asbestos will have a significantly lower risk by virtue of their short employment period. The extremely large number in automobile maintenance arises because of the low relative risk of asbestos disease in that industry. Thus, individuals with as much as four years of employment in automobile maintenance were included in the estimates that gave rise to Table XVIII.

The data in Table XVIII indicate that an enormous number of individuals are likely to have had *some* exposure to asbestos: 27,500,000 since 1940. Of this number, it is estimated that 21,000,000 were alive on January 1, 1980. (This figure was calculated

TABLE XVIII. The Percentage of Asbestos-Exposed Individuals With Lower Exposure*

	Total exposed		Number with	Percentage with
	1940	1940–1979	lower exposure	lower exposure
Primary asbestos manufacturing	23	465	186	38
Secondary manufacturing	30	1,118	493	43
Insulation work	17	167	33	18
World War II		9	2	20
Shipbuilding and repair	157	1,604	362	20
World War II		4,325	1,303	30
Construction trades	426	7,079	1,842	24
Railroad engine repair	69	220	72	25
Utility services	44	584	141	22
Stationary engineers and firemen	295	2,818	834	27
Chemical plant and refinery maintenance	104	1,289	350	25
Automobile maintenance	372	6,044	3,032	47
Marine engine room personnel	34	234	75	28
Totals	1,571	25,956	8,715	32

Lower exposure is characterized as being less than that equivalent to two months employment in an asbestos factory or as an insulator (approximately 2–3 f-yr/ml). It is *not* to be construed as being without risk.

using procedures detailed in the mortality estimates to follow.) Of those exposed, 18,800,000 of the total and 14,100,000 of those alive on January 1, 1980 were estimated to have had an exposure greater than 2–3 f-yr/ml. Such exposures carry significant risk of asbestos disease (as will be detailed subsequently). Further, some risk of asbestos disease exists for the 6,900,000 alive on January 1, 1980, estimated to have experienced lesser exposures.

CANCER FROM OCCUPATIONAL ASBESTOS EXPOSURE: PROJECTIONS 1965–2030

In recent years, considerable data have accumulated that allow projections to be made of the cancer mortality associated with past exposure to asbestos. These include new information on the dose and time dependence of asbestos-related cancers in various occupational circumstances, an increased awareness of the various trades in which possible asbestos exposure occurred in past years, as well as information on the absolute and relative exposures of these different occupational groups. While the relevant data are less complete than desired, they are sufficient to allow estimates of future asbestos-related mortality to be made. These may be useful in directing priorities for appropriate surveillance and interventive activities that might be undertaken.

The Spectrum of Asbestos-Related Cancer

The spectrum of malignant disease that occurs from asbestos exposure is best seen in data from the mortality study of Selikoff et al [1979] on 17,800 insulation workers. This information is shown in Table XIX in which the numbers of deaths, by

TABLE XIX. Deaths Among 17,800 Asbestos Insulation Workers in the United States and Canada, January 1, 1967–December 31, 1976*

Underlying cause of death	Expected[a]	Observed		Ratio o/e	
		(BE)	(DC)	(BE)	(DC)
Total deaths, all causes	1658.9	2271	2271	1.37	1.37
Total cancer, all sites	319.7	995	922	3.11	2.88
Cancer of lung	105.6	486	429	4.60	4.06
Pleural mesothelioma	b	63	25	—	—
Peritoneal mesothelioma	b	112	24	—	—
Mesothelioma, n.o.s.	b	0	55	—	—
Cancer of esophagus	7.1	18	18	2.53	2.53
Cancer of stomach	14.2	22	18	1.54	1.26
Cancer of colon-rectum	38.1	59	58	1.55	1.52
Cancer of larynx	4.7	11	9	2.34	1.91
Cancer of pharynx, buccal	10.1	21	16	2.08	1.59
Cancer of kidney	8.1	19	18	2.36	2.23
All other cancer	131.8	184	252	1.40	1.91
Noninfectious pulmonary diseases, total	59.0	212	188	3.59	3.19
Asbestosis	b	168	78	—	—
All other causes	1280.2	1064	1161	0.83	0.91

*Number of men: 17,800, man-years of observation: 166,853. From Selikoff et al [1979].
[a]Expected deaths are based upon white male age-specific US death rates of the US National Center for Health Studies, 1967–1976.
[b]Rates are not available, but these have been rare causes of death in the general population.
(BE) Best evidence; number of deaths categorized after review of best available information (autopsy, surgical, clinical). (DC) Number of deaths as recorded from death certificate information only.

cause, over a ten-year period, are tabulated along with those expected from national rates. Causes of death are characterized both according to those listed on the certificates of death (DC) and according to the best evidence (BE) available from a review of autopsy protocols, medical records, and pathological specimens. For most causes of death, the agreement is relatively good, but for mesothelioma and asbestosis, considerable differences exist. Because deaths from these causes are rare in the absence of asbestos exposure, their misdiagnosis has little effect upon general population rates. However, as they are common causes of death among asbestos-exposed workers, their misdiagnosis can seriously affect determination of asbestos mortality. Thus, the "best evidence" mortality will be used for the estimate of asbestos-related cancers. However, as we will attribute all excess cancer among insulators to their asbestos exposure (see below), the overall results will not differ greatly from that using certificate of death diagnosis. Higher rates of death at one site (as mesothelioma) will be balanced by lower rates at another (as pancreas).

In addition to mesothelioma and cancer of the lung, cancer of the stomach, colon, rectum, esophagus, larynx, pharyx, buccal cavity, and kidney are each elevated significantly compared with rates expected for these sites in the general population. (This group will be referred to subsequently as "asbestos-related" malignancies.) Opportunity for fiber contact with the epithelial surfaces of the lung and gastrointestinal tract is clearly evident. Exposure to the mesothelial tissue and kidney can occur as fibers readily penetrate into lung lymphatics and reach the pleural mesothelium ("pleural drift") or can be transported to the kidney or peritoneal mesothelium. Similarly, fiber dissemination occurs to other extrapulmonary organs, such as brain, liver, spleen, etc [Langer, 1974]. While excesses at these other sites are not of statistical significance for individual malignancies, the category "all other cancers" is elevated at a high level of significance ($p < 0.0001$), and we will attribute these excess malignancies to asbestos exposure as well. Their contribution accounts for less than 8% of the total excess cancer compared with the contribution of lung cancer, 56%; mesothelioma, 26%; and the other above specified "asbestos-related tumors," 10%.

The Time Course of Asbestos-Related Cancer

The time course of asbestos-related mortality from bronchogenic carcinoma is shown in Figure 1 according to ages for individuals exposed initially between ages 15 and 24, and 25 through 34. As can be seen, the two curves of relative risk, according to age, rise with the *same* slope and are separated by approximately ten years. This suggests that the *relative risk* of developing lung cancer is independent of age and of the pre-existing risk at the time of exposure. In contrast, had one plotted the *added risk* of cancer, the slope and the amount for the group first exposed at older ages would have been two to four times greater than for those exposed at younger ages. If one combines these data and plots them according to time from onset of exposure, the curve of Figure 2 is obtained. A linear increase with time from onset of exposure is seen for 35 to 40 years (to about the time when many insulators terminate employment). After 40 years the relative risk falls significantly, rather than remaining constant after cessation of exposure as might be expected from the linear increase with continued exposure. The decrease is not solely the result of the elimination of smokers from the population under observation as a similar fall occurs for those individuals who were smokers in 1967. (In calculating the relative risk of lung cancer in smokers, smoking-specific data from the American Cancer Society study of one million people were utilized [Hammond, 1966].) Selection processes, such as differing exposure patterns or differing individual

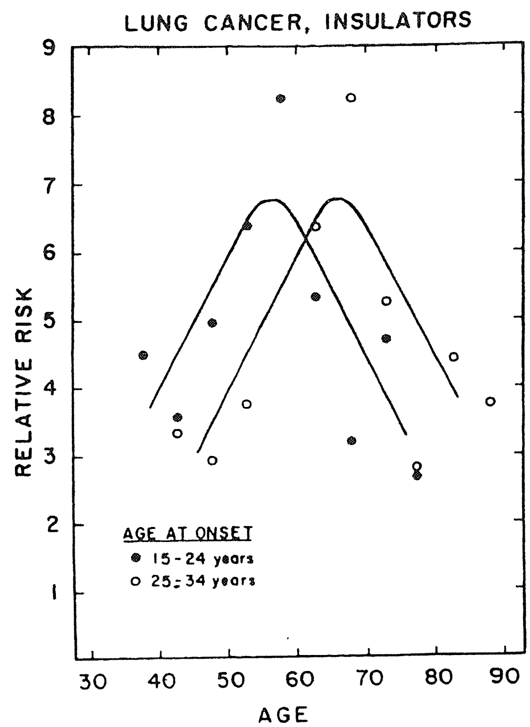

Fig. 1. The ratio of observed to expected deaths from lung cancer among insulation workmen according to age and age at onset of employment.

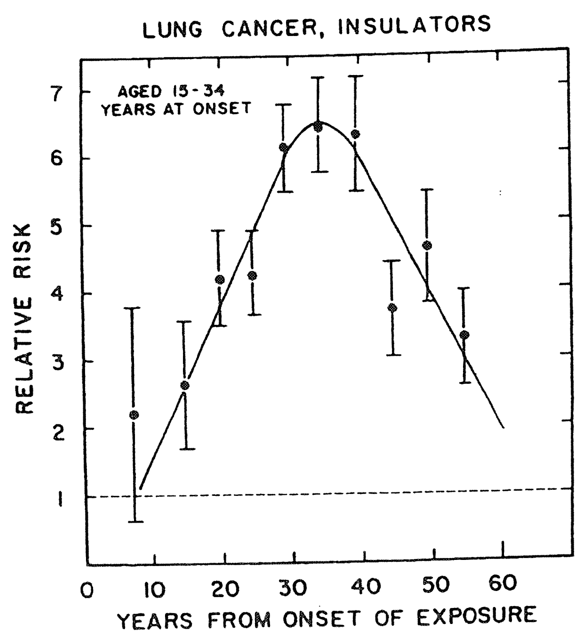

Fig. 2. The ratio of observed to expected deaths from lung cancer among insulation workmen according to time from onset of employment.

biological susceptibilities may play a role, but the exact explanation for the effect is not understood. It is, however, a general phenomenon seen in many mortality studies.

The early portion of the curve of Figure 2 is remarkable in two aspects. Firstly, it shows a linear increase in the relative risk of lung cancer according to time from onset of exposure. This suggests that the dose of asbestos received in a given period of time increases the risk of cancer by an amount that is proportional to that which existed in the absence of exposure. This increased *relative risk* is proportional to the dose of inhaled asbestos, which in turn is proportional to the time worked. Thus, the linear rise in Figure 2. However, the linear rise can occur only if the increased relative risk that is created by a given dose of asbestos continues to multiply the "background" risk for several decades (at least until age 60), even though the background risk will increase tenfold or twentyfold in 30 years. Secondly, the extrapolated line through the observed data points crosses the line of relative risk equal to one (that expected in an unexposed population) very close to the onset of exposure. At most, the line might be adjusted so that it passes through the relative risk of one line at a time from onset of exposure of about ten years. (Note that we are plotting the relative risk of death. Irreversible malignancy would have been initiated several years earlier, since usually one or two years elapse between identification of lung cancer and death, and it is likely that a malignant growth was present, unseen, for at least one or two years before becoming clinically evident.) This means that an increased relative risk appropriate to a given exposure is achieved very shortly after the exposure takes place. However, if there is a low risk in the absence of asbestos exposure, as in young workers, cancers that will arise from that increased relative risk may not be seen for many years or even decades until the background risk becomes significantly greater.

The same two points, 1) that the effect of an exposure to asbestos is to multiply the pre-existing risk of cancer in the exposed population and 2) that the multiplied risk

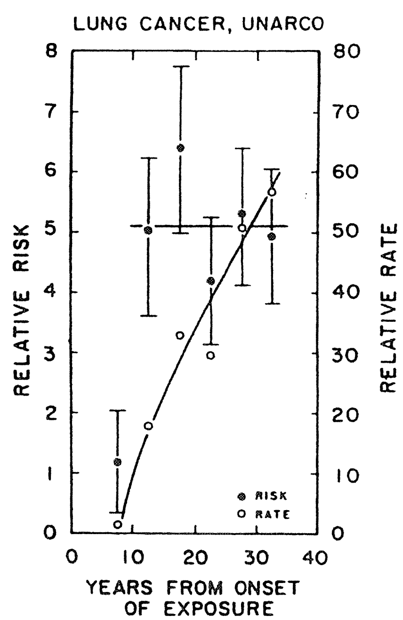

Fig. 3. The ratio of observed to expected deaths from lung cancer and the relative lung cancer mortality rates among asbestos insulation production employees according to time from onset of employment.

becomes manifest in a relatively short time, can also be seen in the mortality from lung cancer in a study of Seidman et al [1979]. Figure 3 depicts the time course of the mortality from lung cancer of a group (UNARCO) exposed for short periods of time, beginning five years after onset of exposure. As 77% were employed for less than two years, exposure largely ceased prior to the follow-up period. As can be seen, a rise to a significantly elevated relative risk occurs within ten years, and then that increased relative risk remains constant throughout the observation period of the study. Furthermore, the relative risk from a specific exposure is independent of the age at which the exposure began. This is seen in Table XX, where the relative risk of death for lung cancer for individuals exposed for less than and greater than nine months is listed according to the age at entrance into a ten-year observation period. Within a given age category, the relative risk is similar in different decades of observation, as we saw before in Figure 3 with the overall data. However, the relative risk also is independent of the age decade at entry into a ten-year observation period. (See lines labelled "All" in each exposure category.) There is some reduction in the oldest groups. This can be attributed to the same effects manifest at older ages in insulators or to relatively fewer cigarette smokers that might be present in the 50-59 year observation groups because of selective mortality.

In the calculation of asbestos-related cancer, the time course of nonmesothelial cancer will be treated as follows. The increase in the relative risk of lung cancer will begin 7.5 years after onset of exposure and increase linearly, following the line of Figure 2 for the number of years a specified group is employed. After a period equal to the average duration of employment, the relative risk will remain constant until 40 years from onset of exposure, after which it will linearly decrease to one over the subsequent three decades. The magnitude of the increase will be equal to that of Figure 2 for insulators and factory employees. The rate of increase for other groups will be proportional to their estimated exposure relative to that of insulators. The same time course

TABLE XX. Relative Risk of Lung Cancer During Ten-Year Intervals at Different Times From Onset of Exposure*

Years from onset of exposure	Age at start of period		
	30–39	40–49	50–59
		Lower exposure (<9 months)	
5	0.00 [0.35]	3.75 (2)	0.00 [3.04]
15	6.85 (1)	4.27 (3)	2.91 (4)
25	–	2.73 (2)	4.03 (6)
All	3.71 (1)	3.52 (7)	2.58 (10)
		Higher exposure (>9 months)	
5	0.00 [0.66]	11.94 (4)	9.93 (8)
15	19.07 (2)	11.45 (5)	5.62 (5)
25	–	13.13 (6)	7.41 (8)
All	11.12 (2)	12.32 (16)	7.48 (21)

*From Seidman et al [1979].

( ) = Number of cases.

[ ] = No cases seen. Number of cases "expected" on the basis of the average relative risk in the overall exposure category.